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Final Technical Report  
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Tectonic Deformation in Southern California  
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## Objectives

Our objectives were to use modern geodetic data, especially those derived from space techniques like Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR), and the Global Positioning System (GPS) to infer crustal deformation in southern California and relate it to plate tectonics and earthquake hazard. To do this, we needed to collect some original data, write computer programs to determine positions of survey markers from geodetic observables, interpret time dependent positions in terms of velocity and earthquake caused episodic displacements, and construct a model to explain these velocities and displacements in terms of fault slip and plate movements.

## Accomplishments:

We made original GPS measurements, especially near NASA VLBI sites at Pasadena, Pinon Flat, Vandenberg AFB, Mojave, Santa Paula, and Palos Verdes, in southern California. We combined these data with existing VLBI data, and with data from the USGS trilateration networks in southern California, to measure the apparent vector velocity of survey markers relative to each other.

We developed computer programs for adjusting VLBI, SLR, GPS, trilateration, and triangulation data to determine the instantaneous displacements due to earthquakes, and the velocity of gradual changes between earthquakes of the relative locations of survey monuments with respect to each other. These programs use prior estimates of the coseismic displacements and the aseismic velocity field in a Bayesian scheme to better estimate the velocities and earthquake displacements. The programs also calculate the covariance matrix that describes the uncertainties of the parameter estimates, and their dependencies upon one another.

We developed a computer model to explain aseismic velocities resulting from slip of seismic faults at depth. The model assumes that the crust is composed of elastic blocks, whose boundaries are the faults that cause earthquakes. The faults are assumed to slip freely, without friction, below some depth called the locking depth. Above this depth, the faults are subject to friction, although they may "creep," or slip at a steady rate, in spite of this friction. The computer model allows us to estimate the translation velocity of the blocks, the rotation rate of

each block about a vertical axis through its center, and the rate of aseismic creep on the upper surface of each fault segment. The relative slip rate and the rate of convergence at depth on the individual faults is also determined, because these quantities are functions of the block parameters mentioned above..

We applied this model to interpret available geodetic data for several parts of the world. These applications were essential to developing the model itself, and gave us a breadth of experience essential for interpreting the deformation in southern California.

## Results

In the Hollister area of central California, both the San Andreas and Calaveras fault display significant creep near the surface. In fact most of the block motion can be explained by creep and deep aseismic slip, so that there is very little elastic deformation of the blocks. Large earthquakes, such as those that occur further to the southeast, are very improbable at Hollister, although they can be expected on the San Andreas fault to the Northwest of Hollister..

The longitudinal valley in Taiwan shows both seismic and geodetic evidence of convergence on dip-slip faults and right lateral strike slip faulting. The measured velocities of surface geodetic monuments indicates that both the convergence and strike slip deformation are confined to a very narrow zone in the longitudinal valley, implying that there is considerable aseismic creep, similar to that observed at Hollister. However, there is some elastic straining of the crust, and large earthquakes are can be expected here. An important difference between the longitudinal valley of Taiwan and the Hollister area is that the block motion in Taiwan includes a strong component of convergence. Taiwan is the only place in the world, to our knowledge, where there is direct evidence of rapid aseismic convergence (that is creep on a dip-slip fault) on land.

Around the Japanese islands, we used VLBI data and excellent triangulation data collected over the last century to determine the pattern of straining caused by plate tectonics in the area. Here the major plate boundary is offshore, so the total plate motion must be inferred from plate tectonic models. The strain rate within the islands is only about half of what would be observed if the Pacific plate rate were moving at the modeled rate relative to the Eurasian plate, and if the plates were locked together at depths shallower than 20 km. Because the plate model has been confirmed by VLBI measurements on Pacific islands, we believe the most likely explanation for the low strain rate on Japan is that the plates are not fully locked above 20 km. Approximately 50 % of the expected plate displacement may occur aseismically. This finding is consistent with the seismic history of Japan over the last 400 years; there have been less seismic moment release than would be expected for a fully elastic plate model.

Near Parkfield in central California, geodetic data are consistent with the observation that surface creep is prevalent to the northwest, but does not occur to any large extent to the southeast of Parkfield. We found weak evidence for an "asperity", or zone where creep is locally inhibited, near the focal zone of the 1966 Parkfield earthquake. However, the data can be fit rather well by a simpler model with no asperity; the asperity is not statistically significant. A consequence is that the geodetic data do not require "characteristic" earthquakes, with a size controlled by the dimensions of the asperity, as suggested by some other investigators.

Further south, on a network crossing the San Andreas fault at Cholame and extending westward through the southern Coast Ranges, the deformation is consistent with a simple model in which the San Andreas fault is locked to a depth of 20 km. The estimated slip rate is entirely consistent with the geologically estimated slip rate of 34 mm/yr. at Wallace Creek, within our geodetic network. In fact the simple elastic model, corrected for direct effects of known historic earthquakes, is consistent with geologic data spanning several thousand year, triangulation data spanning over 100 years, trilateration data spanning about 20 years, and GPS data spanning just 4 years. We conclude that any temporal variations of strain rate are no greater than 20% on any of these time scales. Taken together, these measurements provide the first direct evidence that so tightly constrains the amount of inelastic strain in the crust.

In the broader southern California region, we find the strain to be much more widespread in the transverse ranges than further north or further south. The strain pattern here is not consistent with a simple model of elastic strain resulting from slip on locked faults, unless the locking depth exceeds the thickness of the crust. As it is unlikely that the faults are locked to such great depth, we believe the displacement is shared among many smaller faults, and that the slip rate on the Mojave section of the San Andreas itself is considerable less than that on the Cholame section. An implication is that the seismic hazard is spread more uniformly throughout southern California, and closer to the populated regions of Los Angeles and Orange counties.

## **Publications:**

The following papers resulted from work supported by this grant:

Matsu'ura, M., D. Jackson, and A. Cheng, Dislocation model for aseismic deformation at Hollister, California, J. Geophys. Res., 91, 12,661-12,674, 1986.

Cheng, A., D. Jackson, and M. Matsu'ura, Aseismic crustal deformation in the Transverse Ranges of southern California, Tectonophysics, 144, 159-180, 1987.

Sung, L.Y., and D. Jackson, Geodetic evidence of the seismic potential at Parkfield, California, Geophys. Res. Lett., 15, 820-823, 1988.

Shen, Z.K., and D.D. Jackson, Global Positioning System reoccupation of early triangulation sites: tectonic deformation of the southern Coast Ranges, J. Geophys. Res., 98, 9931-9946, 1993.

Feigl, K., D. Agnew, Y. Bock, D. Dong, A. Donnellan, B. Hager, T. Herring, D. Jackson, T. Jordan, R. King, S. Larsen, K. Larson, M. Murray, Z. Shen, and F. Webb, Measurement of the velocity field of central and southern California, 1984-1991, J. Geophys. Res., in press, 1993.